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14. ABSTRACT

Laminar to turbulent transition is a critically important process in hypersonic vehicle design. Higher thermal loads, by half an order of magnitude or more, result from the increased heat transfer due to turbulent flow. Drag, skin friction, and other flow properties are also significantly impacted. Turbulent transition occurs through the genesis, growth, and propagation of isolated local turbulence patches, known as turbulent spots. H.W. Emmons (1951) was the first to propose that laminar boundary layers break down through the convergence of spots, after observations of a water-table analogy to air flow. Spot formation has been studied extensively in subsonic flows, notably by Narasimha (1957), Dhawan and Narasimha (1958), Chen and Thyson (1971), Abu-Ghannam and Shaw (1980), Narasimha (1985), and Simon (1995).

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Turbulent Spot Observations within a Hypervelocity Boundary Layer on a 5-degree Half-Angle Cone

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Nomenclature

C_{le}	=	U_{le}/U_e normalized turbulent spot leading edge propagation rate
C_m	=	U_m/U_e normalized turbulent spot trailing edge propagation rate
C_{te}	=	U_{te}/U_e normalized turbulent spot centroid/peak propagation rate
M_e	=	boundary layer edge Mach number
$\dot{q}$	=	heat flux (transfer rate)
$\dot{q}_L$	=	laminar heat flux
$\dot{q}_T$	=	turbulent heat flux
Re_x	=	unit Reynolds number
Re_{ex}	=	boundary layer edge unit Reynolds number
T_e	=	boundary layer edge temperature
T_w	=	wall temperature
U_e	=	boundary layer edge velocity
α	=	turbulent spot spreading angle

I. Introduction

Laminar to turbulent transition is a critically important process in hypersonic vehicle design. Higher thermal loads, by half an order of magnitude or more, result from the increased heat transfer due to turbulent flow. Drag, skin friction, and other flow properties are also significantly impacted. Turbulent transition occurs through the genesis, growth, and propagation of isolated local turbulence patches, known as turbulent spots. H.W. Emmons (1951) was the first to propose that laminar boundary layers break down through the convergence of spots, after observations of a water-table analogy to air flow. Spot formation has been studied extensively in subsonic flows, notably by Narasimha (1957), Dhawan and Narasimha (1958), Chen and Thyson (1971), Abu-Ghannam and Shaw (1980), Narasimha (1985), and Simon (1995).

The first turbulent spots in a supersonic boundary layer were detected by James (1958) on free-launched projectiles using spark shadowgraphs with a conical light field, characterizing both propagation speed and growth rate for free-stream Mach numbers from 2.7 to 10. James was able to surmise that the differences were likely to be small between turbulent-spot propagation in subsonic and supersonic flow. Around the same time, Deissler and Loeffler (1958) studied supersonic transition on a flat plate. Since then, a number of studies of spots in supersonic and hypersonic flows have been carried out, with reviews given by Fiala et al. (2006) and Mee (2002).

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II.   Recent Work on Supersonic Flows

Clark (1993) and Clark et al. (1994) studied the propagation of naturally-occurring turbulent spots in turbine-representative flows from Mach 0.24 to Mach 1.86 using thin-film heat transfer gauges to track individual spots. Clark characterized turbulent spot leading-edge, trailing-edge, and "mean" or centroid velocities, and also measured the spreading angle at several Mach numbers in this range. Clark also examined the propagation of turbulent spots in mild and strong pressure gradients both favorable and adverse, and developed software routines for turbulent spot propagation.

Hofeldt (1996) and Hofeldt et al. (1998) also studied spots in flows from Mach 0.24 to Mach 1.86 using thin-film heat transfer gauges, examining the effect of gas-to-wall temperature ratios as well as the "overhang" region—the turbulent spot's spatial extent in the downstream direction is greater further from the plate, though most numerical simulations ignore this fact—and becalmed regions of turbulent spots. Hofeldt was able to show that the becalmed region behind a turbulent spot is in fact consistent with the growth of a new laminar boundary layer.
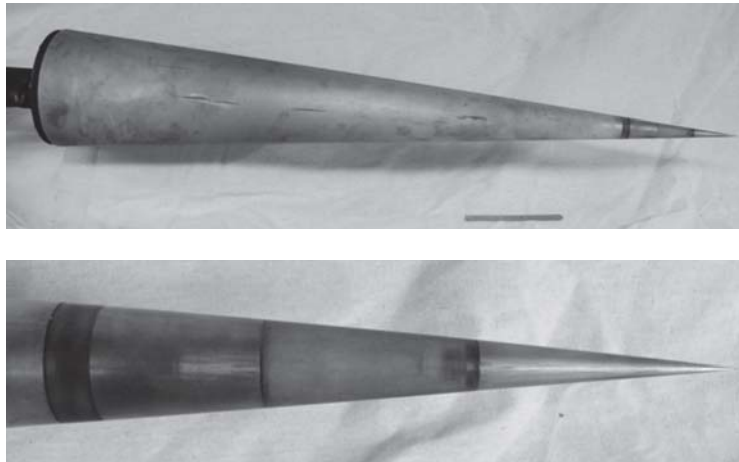
Figure 1. Top: Aluminum cone, 1m in length, instrumented with 80 thermocouples in 20 rows. Bottom, from right to left: molybdenum tip, plastic holder with 316L stainless steel 10 micron porous section, aluminum cone body.

Mee and Goyne (1996) performed experiments to detect turbulent spots on a flat plate in free-piston shock tunnel flows of Mach 5.6 to 6.1 at low, mid-range, and high unit Reynolds numbers (Re_x between 1.6×10^6 m^{-1} and 4.9×10^6 m^{-1}) using thin-film heat transfer gauges. They were able to detect turbulent spot activity and measure intermittency, and recommended further tests to measure convection speeds and spreading rate. Mee (2001) and Mee (2002), using the same facility as Mee and Goyne (1996) with new instrumentation, measured the effect of using 2 mm-high boundary layer "trips" behind the leading edge of a flat plate in Mach 5.5 to Mach 6.3 free-piston shock tunnel flow and found them to be capable of advancing the transition location. Mee measured a spot growth angle of $3.5° \pm 0.5°$.

Fiala et al. (2006) have recently measured turbulent spots progressing on a blunt cylindrical body with spherical nose in hypersonic flow (Mach 8.9 free stream; Mach 3.74 at the edge of the boundary layer) using a series thin-film heat transfer gauges. They were able to detect clear turbulent spot activity and measure intermittency by comparing heat transfer time histories from axial gauges in the intermittent region of the body, and also visualize the passing signals from individual spots with a circumferential array of gauges. Computational studies of spot propagation in supersonic flows have been carried out by Chong and Zhong (2005), Krishan and Sandham (2006), and Jocksch and Kleiser (2008). Selected results of experiments and computations are given in Table 1.

III.   Experiment

The facility used in all experiments for the current study is the T5 hypervelocity reflected shock tunnel; see Hornung 1992 and Hornung and Belanger 1990. The model is a 5 degree half-angle aluminum cone similar to that used in a number of previous experimental studies in T5, 1m in length, and is composed of three sections: a sharp tip fabricated of molybdenum, a mid-section containing a porous gas-injector section, and the main body instrumented with a total of 80 thermocouples evenly spaced at 20 lengthwise locations. These thermocouples have a response time on the order of a few microseconds and have been successfully used for boundary layer transition location in Adam (1997) and Rasheed (2001).
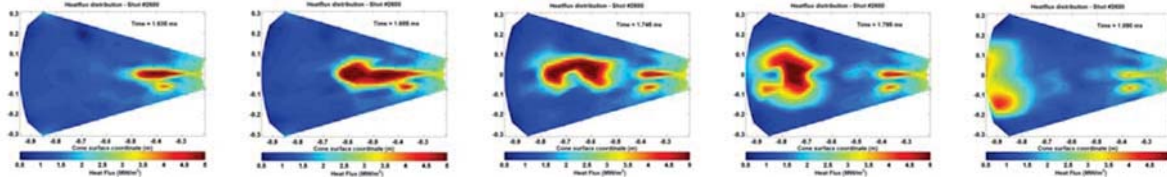
Figure 2. Time-resolved heat transfer rate plots of the developed cone surface. In these frames from a heat flux "movie", a turbulent spot can be seen growing as it propagates down the surface of the cone. Flow in each image goes from right to left.
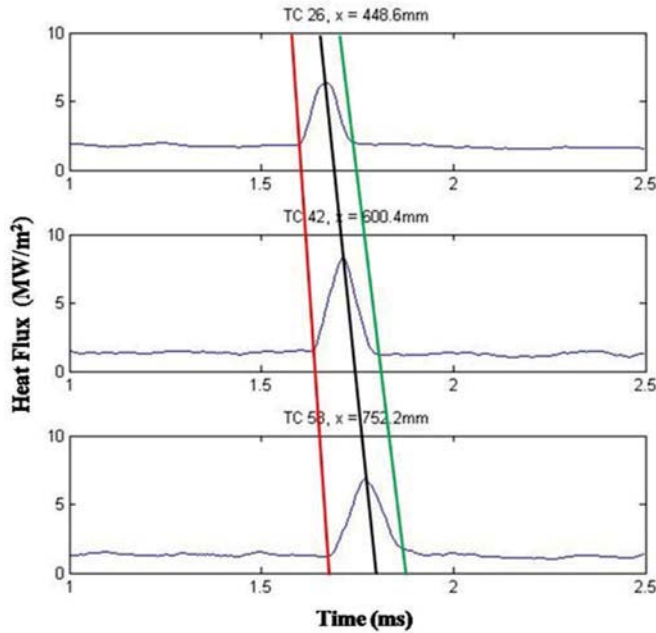

Figure 3. Smoothed heat transfer traces from three co-linear thermocouples, at x-displacements from the cone tip of 448.6mm, 600.4mm, and 752.2mm, respectively, under the propagating spot depicted in Figure 2. The spot's leading edge (red), centroid (black), and trailing edge (green) velocities may be calculated from the signals.

The conical model geometry was chosen because of the wealth of experimental and numerical data available with which to compare the results from this program. A photograph of the cone model is shown in Figure 1. The porous injector section is 4.13 cm in length and consists of sintered 316L stainless steel, with an average pore size of 10 microns. A detail view of the tip and porous injector section is shown in the bottom of Figure 1. The injector was not used in the present tests and has been shown not to trip the boundary layer when gas is not injected.

A method of presenting time- and spatially-resolved heat flux data has been developed and implemented, which allows the presentation of a "movie" of heat flux over the entire instrumented surface of the cone during the test time (see Figure 2). A similar method has allowed the observation of turbulent "spots" observed in lower-speed flow (Clark 1994). Figure 3, depicts the results from shot 2680, and the trajectories shown indicate how we have characterized spots by leading edge, trailing edge and centroid (peak) velocity. Measurements for three such spots, at a Mach number of about 5.1, are presented in Table 1 as fractions of the respective boundary layer edge velocities, and compared with other experimental and computational supersonic and hypersonic results at similar and disparate boundary layer edge conditions.

	Shot 2680	Shot 2654	Shot 2645	Z&H 1996	Fiala et al 2006	Mee 2002	Clark et al 1994	K&S 2006	J&K 2008	J&K 2008
M_e	5.11	5.04	5.07	8.02 [b]	3.74	6.1	1.86	6	5	5
U_e m/s	3875	4087	3995	[a]	1300 [b]	3370	580 [b]	[a]	[a]	[a]
Re_{ex} /m	7.42×10^6	6.63×10^6	5.18×10^6	[a]	2.69×10^6	4.9×10^6	16.0×10^6	[a]	[a]	[a]
T_w/T_e	0.195	0.169	0.180	4.38 [b]	0.97 [b]	0.371 [b]	1.23 [b]	7.00	5.19	1.00
C_{le}	0.96 ±0.07	0.93 ±0.08	0.92 ±0.04	0.98	0.81	0.90 ±0.10	0.83 ±0.04	0.89	0.96	0.89
C_m	0.78 ±0.07	0.77 ±0.08	0.82 ±0.04	–	–	–	0.64 ±0.02	0.76 [c]	–	–
C_{te}	0.55 ±0.07	0.56 ±0.08	0.69 ±0.04	0.68	0.40	0.50 ±0.10	0.53 ±0.02	0.53	0.54	0.23
a: value not reported										
b: calculated from other reported values										
c: spot "wing tip" convection velocity										

Table 1. The present experimental (Mach 5 cone) results are compared with other supersonic and hypersonic experiments (Zanchetta and Hillier 1996, Fiala et al. 2006, Mee 1996, and Clark et al. 1994) and computations (Krishnan and Sandham 2006 and two results from Jocksch and Kleiser 2008) performed at a range of conditions.

At lower Mach numbers, such as the results of Clark et al. (1994), the subsonic (first) mode is the dominant linear boundary layer instability mechanism. At hypersonic Mach numbers (>4), instabilities in the second (Mack) acoustic mode dominate the boundary layer transition mechanism. For cold wall hypervelocity flow, which is characteristic of high enthalpy shock tunnels like T5 and T4, the first mode is expected to be damped and the higher inviscid modes are amplified, so that the second mode would be expected to be the only mechanism of linear instability.

IV. Conclusion

Time- and spatially-resolved heat transfer traces in a high-enthalpy hypervelocity flow on a 5-degree half angle cone are measured with thermocouples. Turbulent spots are observed propagating in both heat transfer traces and heat flux "movies" of the developed cone surface. These observations are used to calculate turbulent spot convection rates, which are compared with previous experimental and computational results. Although the present results were obtained at different conditions from past experiments, the normalized spot propagation results for Mach 5 flow are found to be in good agreement with past supersonic and hypersonic experiments, as well as computations at similar conditions. While the spot spreading angle α has not been discussed in this abstract, and the design of the experiment precludes precise measurement of this parameter, preliminary bounding values have been obtained. For example, for shot 2654, we estimate $2° < \alpha < 13°$, which is not inconsistent with the reported value of $3.5° \pm 0.5°$ of Mee (2002).

Acknowledgments

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